Passive mode locking of buried heterostructure lasers with nonuniform current injection

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In this letter we report on a novel method to passively mode lock a semiconductor laser. We present experimental results of GaAlAs buried heterostructure semiconductor lasers with a split contact coupled to an external cavity. The split contact structure is used to introduce a controllable amount of saturable absorption which is necessary to initiate passive mode locking. Unlike previous passive mode locking techniques, the method presented does not rely on absorption introduced by damaging the crystal and is consequently inherently more reliable. We have obtained pulses with a full width at half-maximum of 35 ps at repetition frequencies between 500 MHz and 1.5 GHz.

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Ultrashort optical pulses generated with semiconductor lasers are of great interest for applications such as very fast optical signal processing and high bit rate communication. Pulses in the picosecond range have been obtained by such diverse methods as microwave current injection,[1] pumping with short electrical pulses,[2] or by mode locking the lasers in an external optical cavity. Mode locking has been achieved either by modulating the gain at a frequency corresponding to the cavity roundtrip time (active mode locking[3–12]) or by placing a nonlinear element such as a saturable absorber in the cavity (passive mode locking[13–17]); the shortest pulses to date have been generated by the passive mode locking technique.[15,17] The usually quoted necessary condition to obtain passive mode locking with an homogeneously broadened laser is that the absorbing medium saturate much more easily with optical intensity than the gain medium.[18] In order to passively mode lock a semiconductor laser one has to place an absorber with this desired characteristic in the external optical cavity. It seems promising to use unpumped GaAs as the absorber, i.e., to pump only part of the semiconductor laser and to use the unpumped section as the absorber. Unfortunately measurements of the gain as a function of the carrier density in GaAs lasers[19] indicate that the absorption in unpumped GaAs does not saturate more easily than the gain. However, an absorber with the desired characteristic can be obtained by damaging the GaAs crystal and introducing defects. These defects are optically absorbing and can be saturated very easily. One method for obtaining such defects (dark line defects) is to age a laser to the point of severe degradation. Pulses as short as 1.3 ps have been achieved with this technique.[17] Unfortunately the concentration of these defects increases at this stage rapidly and short pulses are only obtained with lasers at the verge of failure. Another method is to introduce these saturable defects by damaging the crystal near one mirror through proton bombardment[20] and 15-ps-long bursts of subpicosecond pulses have been generated by this technique.[15]

In this letter we report on a different method for producing picosecond pulses which does not rely on any damage of the crystal and which is consequently inherently more reliable. The picosecond pulses are generated with a laser with nonuniform current injection obtained through a split contact structure.[21] We have shown that for a complete description of such an optoelectronic device the electrical aspect has to be included and that the necessary condition for small-signal instability is less restrictive than the one quoted above; indeed, we have shown that a nonuniform pumped laser (with a linear gain dependence on carrier density and a bimolecular recombination rate) can either be bistable or pulsating depending on the biasing condition.

The GaAlAs buried heterostructure lasers with a split contact were fabricated in our laboratory as described earlier.[21] Under the usual operating conditions one section is heavily forward biased (gain section) and the other section is only slightly biased thus introducing loss (absorber section). An SiO antireflection (AR) coating was applied to one mirror facet in order to facilitate the coupling to the external optical cavity and to suppress the effects of the short cavity. The gain section was pumped with a constant current (I_1) and the absorbing section was biased with a voltage source (V) with a resistor in series (R_2) as shown in Fig. 1. The external optical cavity consisted of a 0.3-N.A. microscope objective which collimated the light and of a dielectric mirror with a reflectivity of 90%. The light emitted from the AR coated

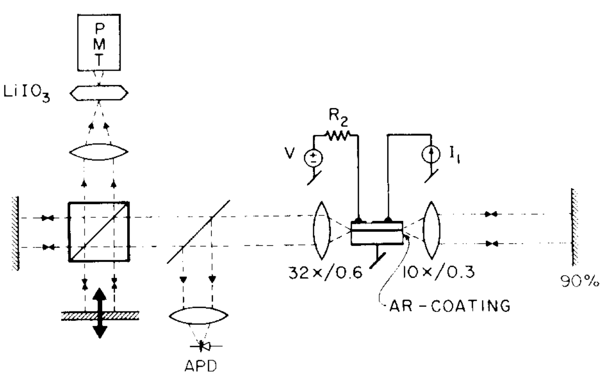

FIG. 1. Experimental arrangement of a double contact laser which is passively mode locked in an external optical cavity. Also shown is the pulse measurement system consisting of an avalanche photodiode (APD) and an autocorrelator employing a 3-mm-long $LiIO_3$ crystal as the nonlinear medium.

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facet was reinjected into the active region by careful adjustment of the mirror and the lens. The degree of reinjection was monitored by measuring the voltage across the absorbing section which greatly facilitated the alignment procedure. The optical cavity length was varied between 10 and 30 cm corresponding to a pulsation frequency between 500 MHz and 1.5 GHz. From the changes in the threshold current of the uniform pumped laser we estimated that the mirror reflectivity was reduced to around 1% to 3% after deposition of the AR coating and that the effective mirror reflectivity in the external cavity was around 6%. The light emitted from the back facet of the laser was collimated and focused on a wide bandwidth avalanche photodiode (AEG-Telefunken S171P) with a calibrated rise time of 120 ps. The width of the optical pulses was measured with an autocorrelator employing phase matched second harmonic generation in a $LiIO_3$ crystal.[22] A photomultiplier tube was used to detect the relatively weak frequency doubled signal which was of the order of a few femtowatts at a wavelength of 440 nm.

The average light output as a function of current through the gain section (I_1) is shown in Fig. 2. As reported earlier[23] the characteristic depends dramatically on the biasing resistor R_2 which is in series with the absorber section. When R_2 is large ($R_2 = 200\ \mathrm{k}\Omega$), a condition to which we will refer as current biasing, the pump rate is constant and the device displays bistability with a large hysteresis. When R_2 is small ($R_2 = 330\ \Omega$), i.e., voltage biasing, the carrier density in the absorber section is clamped and the device displays a region with a very high differential quantum efficiency (light jump). It is a unique feature of semiconductor diode lasers that the carrier density inside the active region can be clamped from the outside by biasing the diode with a constant voltage source. We have shown earlier[21] that through this voltage biasing the laser can be forced into operating points not attainable with current biasing. Figure 3 shows the microwave spectrum of the photocurrent generated in the avalanche photodiode for voltage biasing (upper half) and current biasing (lower half). In the current biasing mode the laser light output is stable and only some small noise peaks can be seen at multiples of the frequency corresponding to the roundtrip time. Through voltage biasing the laser can be forced to operate in an unstable regime where it self pulsates.[21] The pulsation rate is around 500 MHz for this specific case corresponding to a cavity length of 30 cm. This rate is fairly stable having a linewidth of less than 20 kHz. Harmonics up to 4 GHz can be observed and they are limited by the bandwidth of the photodiode. The shortest pulses were observed when the laser was biased just above the light jump and the pulses observed with a sampling oscilloscope were detector limited 150 ps long with a modulation depth close to 100%.

A typical second order correlation trace is shown in Fig. 4. The laser voltage biased and operated at a current I_1 just above the light jump in a cavity with a length of 30 cm. The correlation trace consists of a relatively broad peak with a width of $\Delta\tau_1 = 53$ ps upon which is superimposed a series of extremely sharp spikes with a width of $\Delta\tau_2 = 1.4$ ps and a separation of $t_2 = 5.5$ ps. Since the second order correlation has an intensity ratio of 1:2:3 this trace corresponds in the

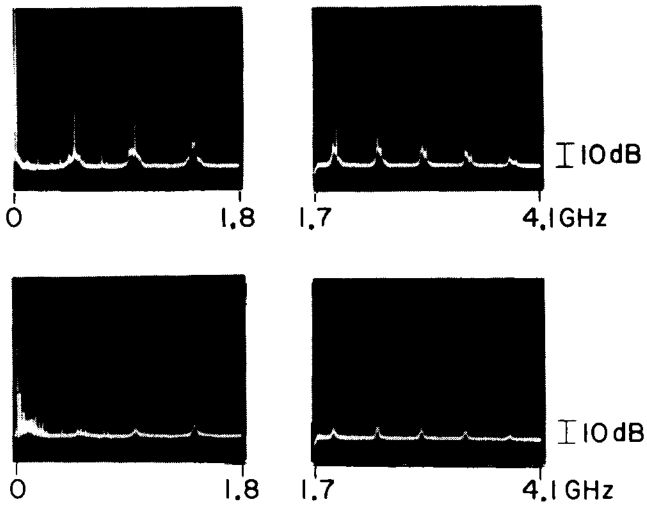

FIG. 3. Typical microwave spectrum of the optical output as measured with the avalanche photodiode (APD) for voltage biasing (top half) and current biasing (lower half) for a cavity length of 30 cm.

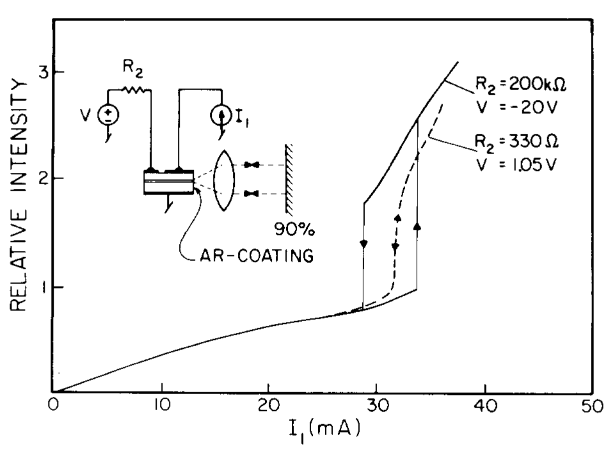

FIG. 2. Light-current characteristic of a double contact laser in an external optical cavity for current biasing ($R_2 = 200\ \mathrm{k}\Omega$; $V = -20$ V) and voltage biasing ($R_2 = 300\ \Omega$; $V = 1.05$ V) as measured with the avalanche photodiode (APD).

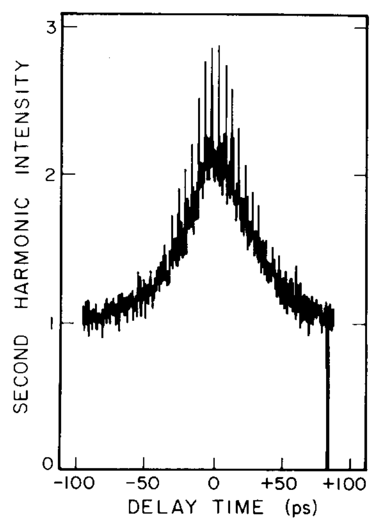

FIG. 4. Autocorrelation trace of the passively mode locked diode laser. FWHM of the pulse is around 35 ps.

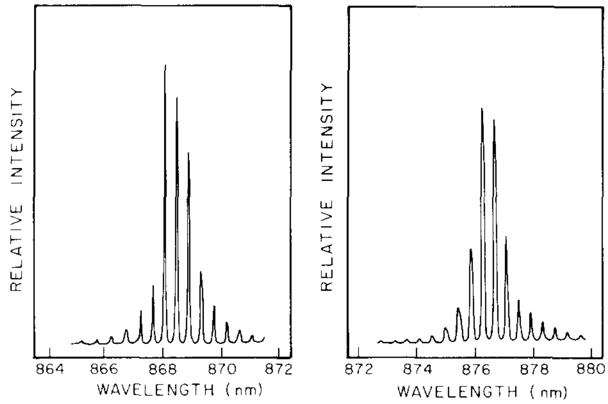

FIG. 5. Optical spectrum of the laser with a segmented contact placed into an external cavity. On the left side is the spectrum shown when the absorber section is current biased (stable output) and on the right side is the spectrum shown with the absorber section voltage biased (pulsating output).

time domain to a pulse with some noisy periodic substructure.[24] Assuming Gaussian shapes and transform limited pulses we obtained a full width at half-maximum of $\Delta t_1 = 37$ ps and a spectral width of $\Delta \nu_1 = 12$ GHz ($\Delta \lambda_1 = 0.3$ Å). This means that around 20 longitudinal modes of the external cavity are phase locked. The separation t_2 between the spikes corresponds to the round trip time in the semiconductor cavity ($L = 200\ \mu$m). Under stable operating condition these lasers typically emitted all their power into one single longitudinal mode. After applying the AR coating they operated multilongitudinal as shown in Fig. 5 on the left side with a separation of 4.5 Å corresponding to the semiconductor length L. The width of the modes was 0.3 Å, limited by the resolution of the spectrometer. Under mode locking conditions the modes broadened appreciably to around 0.9 Å as can be seen in Fig. 5 on the right half. Even if we take the finite resolution of the spectrometer into account the modes are broader than expected from transform limitations. This could be explained by a frequency chirp due to the variation of the carrier density in the active region during one pulse. The separation of the clusters of locked modes corresponds to the separation in time (5.5 ps) of the fine structure of the second order correlation and the overall width of the spectrum (10 Å) corresponds to the width of the fine structure.

In conclusion, we have shown that nonuniform pumping of a semiconductor laser is an excellent means of introducing saturable absorption in a controllable way. This absorption can lead to bistability or pulsations depending on the biasing conditions. We utilized this scheme to generate picosecond pulses by passively mode locking this device in an external optical cavity. This passive mode locking technique is inherently reliable since it does not rely on absorption introduced by damaging the GaAs crystal. By using a large optical cavity structure the coupling to the external cavity could be made stronger and easier and by introducing a bandwidth limiting element[13,25] transform limited pulses should be obtained.

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